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Review

Blue jet models and associated lightning flashes

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Abstract Blue jet, a transient luminous event propagating upward from the top of active thundercloud is yet a mysterious to scientists A few models have been suggested for explaining this unusual phenomenon In this paper we have critically examined the reported results on blue jet and the models subsequently developed for this optical phenomenon, as well as its relationship to intra cloud (IC) and cloud to ground (CG) lightning discharges The contribution of the quasi-electrostatic field and the mechanisms involved in the formation of blue jet with certain limitations of pre-discharge model, runaway discharge model and attachment-controlled ionizing wave model have been reviewed besides their relation to lightning flashes of both IC and CG types Scopes for further investigations are also indicated

Keywords Blut jet, lightning, sprites, transient luminous event

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Plan of the Article

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1. Introduction

Transient luminous events (TLE) constituting a wide range of optical and electromagnetic phenomena occur from the active thundercloud tops to the heights of 40 to 90 km [1,2]. Although marginally visible to the naked eye under proper viewing conditions, TLE were not observed or accounted for previously, with the exception of reports by high flying pilots [3]. Nicknamed 'red sprites', 'elves' and 'blue jets', these discharges were first noted by Franz *et al* [4]. Since their discovery they have been photographed from ground stations, aircraft and the space shuttle [5–7]. Though several theories have been suggested to account for the generation of TLE [6] yet none of them seems to be conclusive [8]. During the last few years, the importance of TLE to the global electrical circuit and to the chemistry of the upper atmosphere including the ozone layer has been recognized widely.

Blue jet, discovered during the 'Sprites 94 aircraft campaign' [9,10] are beams of blue light propagating upwards in many times from the tops of active thunderstorms. The typical blue jet documented by Sukhorukov and Stubbe [11] was quasi-vertical narrowly collimated and not aligned with the geomagnetic field. They appeared from the apparent top of a very high anvil cloud (~18 km) and had a terminal altitude ~40 km with a vertical velocity ~ 100 km/s. The jet velocity was independent of height and was about the same for different events. A hemispherical 'shock front' has been found beyond the terminus of some jets traveling to ~50 km at the same velocity as the earlier rising portion of the jet while some other events, having essentially lower terminal altitudes (<26 km), were also captured during the same observation period and named as 'blue starters' [12]. Several models of the blue jet have been proposed and there is an agreement among them that the blue jet is a likely manifestation of the breakdown phenomenon in the stratosphere. Two models, one by Pasko *et al* [13] and the other by Sukhorukov *et al* [14], are based on the mechanism of the conventional air breakdown. On the other hand, Roussel-Dupre and Gurevich [15] and Taranenko and Roussel-Dupre [16] put forward the runaway breakdown concept for high-altitude flashes. As the nature of the blue jets is largely confusing, we have attempted in this paper to make an assessment of different models proposed so far for investigating the behavior and characteristics of this unusual phenomena.

2. Background

During the summer of 1994, Wescott and associates [17–19] pointed out the existence of jets. They called them blue jets when they were able to record a very active thunderstorm in Arkansas, USA, using both low-light-level monochrome and color video cameras. The video was collected in nighttime using two aircraft that were flying around the thunderstorm. During this flight, color video imagery established that the jets are blue in color. A total of

52 jets were observed during a 20-minute time span. The jets developed over several video frames, with a characteristic time of the order of 100 ms. The propagation speeds were similar to that of a step leader process (*i.e.* ~10^5 m/s). The spectacular multiple close-up images of these jets completely overshadowed the single, poorly resolved jet observation from the space shuttle. During this flight blue starters, an upward moving luminous phenomenon related to blue jets, were also discovered [19]. It is believed that "rocket lightning" reported by scientists [20–23] is the same phenomenon as a 'blue jet' [17–19].

Throughout the historical scientific literature, there are many eyewitness accounts of unusal 'lightning' observed in the clear air above nighttime thunderstorms [20]. They are described as "a luminous trail shot up to 15 degrees or so, about as fast as, or faster than, a rocket" [21], "a long weak streamer of a reddish hue" [24], "flames appearing to rise from the top of the cloud" [25], or "the discharged assumed a shape similar to roots of a tree in an inverted position" [26]. As because these eyewitness reports of unusual lightning appearing above thunderstorms were not captured on film, the lightning science community ignored them. The number of reports increased as the view point moved up from the ground to aircraft and further towards space. Vonnegut [27] maintained a keen interest in various types of lightning phenomena produced by thunderstorms and tornadoes. Most of the pilots were reluctant for reporting officially the things which they had observed, because the scientific community, the Air Force and the airlines were skeptical of "upward lightning". Scientists [28–31] reported and examined the unusual luminous phenomena that pilots saw above thunderstorms. The pilots pointed out analogies to draw a verbal picture of "upward lightning". Although these are credible eyewitnesses for predicting severe weather phenomena, their accounts did not inspire much for a general search of the phenomena.

3. Typical characteristics

Blue jets are narrow cones of blue light usually propagating upward from the cloud tops at speeds of about 100 km/s to terminal altitudes of about 40 km. The results of a refined analysis of these optical phenomena and their relationship to cloud to ground (CG) and intra cloud (IC) lightning including their apparent color and possible mechanisms for their production is a matter of great interest today. In a thunderstorm where more than 50 events were seen from aircraft during night time of July 1994, about half of the blue jets occurred in a cluster [10]. At the time of the blue jet occurrences hail of 7 cm diameter fell in those two storm cells, according to the report. One other blue jet was also observed over an intense multi cell storm. Comparison to CG lightning strokes showed that blue jets were not coincident with either positive or negative CG strokes but they occurred in the same general area. It was further noted that cumulative distributions of the negative CG strokes in ±5 s before and after the jet and within a radius of 15 km showed a significant reduction in the flash rate for 2 s following the event. From careful analysis of color TV signal levels and also from calculations of quenching and atmospheric transmission Wescott *et al* [32] concluded the presence of significant ionization in the jets. Theoretical works by others [33] suggested that the mechanism for their production is a streamer. However, there remain many discrepancies between the observations and the theories developed.

4. Blue jet theories

The blue jet models are classified basically on three apsects, *viz.* (i) Predischarge model, (ii) Runaway discharge model and (iii) Attachment-controlled ionizing wave model.

4.1. Pre-discharge model:

Pasko *et al* [13] suggested that the blue jets may be developed during the accumulation of the positive charge at the top of the cloud *i.e.* in the presence of the upward quasi-electrostatic field above the cloud. This is in fact a numerical realization of a positive streamer. In their model the authors assumed that a positive charge of 375 C builds up with a time scale of 1 s at 20 km altitude, in a form of a spherically symmetric Gaussian distribution with a spatial scale of 3 km and then dissipates with a time constant of 0.5 s. The result revealed that the streamer velocity was 40 km/s at 24 km altitude and 100 km/s at 35 km altitude. At these altitudes the electron density was 10^3 cm^{-3} and 180 cm^{-3}, respectively. The jet terminal altitudes (~50 km) is due to either the chosen bound on the jet conductivity profile or the chosen dissipation time constant. Though the model reproduced the form of jet to some extent properly, yet predicts too large absolute intensities of the optical emissions.

The numerical model developed by Pasko *et al* [13] is not fully self-consistent as in this model the attachment is ignored and a bound on the growth of the electron density is placed too low. For streamers in non-attaching gases, the electron density created in the streamer front and conductivity remains almost consant, which, however increases slowly due to the recombination. For air, the attachment is the controlling agent for the electron density and the electric field in the streamer and hence cannot be ignored. Pasko *et al* [13], referring to Lowke [34], suggested that the detachment due to metastable O_2 may be extremely effective and thus may conserve created electrons. However, the effective reduction of the breakdown field E_c by a factor of 6 as computed by Lowke [34], demands extremely large current densities, at least four orders of magnitude higher than in the pre-discharge model. For current densities of the latter model, the scaling in Lowke's result reveals the negligible effect of the detachment on E_c. It appears that the electric field in the body of the jet is too large, $E \approx E_c$. This lead to an overestimate of the jet brightness by several orders of magnitude in the model. In fact, this provides yielding similar intensities for red and blue lines. In comparison to other models, the model [13] needs the largest cloud charge and back-ground field, $E \approx E_c$, as the postulated conductivity of the jet and the computed field enhancement at the tip are two small. Thundercloud charge distributions extended horizontally, consisting of large number of charge centres at altitude <20 km producing the required large field which is equivalent to that of a monopole of 300–400 C at that altitude. Further, the rnaway electrons are likely to contribute to the production of ionization in the head of the blue jets exhibiting a similar streamer development but with different details of the optical spectra.

It should be pointed out here that the idea of the pre-discharge concept is interesting as the concept can explain successfully the absence of a clear association of the blue jets with strong discharges of CG type.

4.2. Runaway discharge :

Rousell-Dupre and Gurevich [15] and Taranenko and Roussel-Dupre [16] proposed runaway breakdown theory for high-altitude flashes. This theory encompasses both the blue jets and red sprites. Roussel-Dupre and Gurevich [15] argued that if the gamma ray emissions observed at an altitude >30 km [35] can be directly linked to the sprites and jets, then any model of the high altitude flashes based on conventional air breakdown mechanism should be ruled out. The runaway model suggests a downward quasi-electrostatic field, establsihed above the cloud either after an IC discharge annihilating upper positive and lower negative charges or after a positive CG discharge. The threshold electric field required to initiate the electron avalanche, stimulated by cosmic ray secondaries, is by a factor of 10 lower than the conventional breakdown threshold [36].

This concept of tropospheric lightning initiation [36] has been supported to some extent by the thunderstorm electric field soundings [37]. On the other hand, quasi-electrostatic fields close to the conventional breakdown threshold have not yet been measured. In fact, no data are available on the short-time electric field transients with magnitudes around the local breakdown field. It should be mentioned that both numerical realizations of the runaway theory for high-altitude flashes [15,16] do not address explicitly the blue jet specific feature documented by Sentman and Wescott [9] and Wescott *et al* [10]. Particularly, the computed primary emissions cover the altitude range from 30 km to 60 km. Taranenko and Roussel-Dupre [16] assumed that jet motion may be only a visual effect of the combination of the primary, very short (~ 0.13 ms) emission with a long-time emission owing to the recombination of the created ions. They gave a possible explanation for the observed velocity that lies in the development of the source electric field configuration. Truly, the runaway breakdown mechanism is very sensitive to the parameters of the tropospheric discharge, *e.g.*, the runaway model of red sprites of Bell *et al* [38], based on the model of the positive CG discharge, yields emissions at z > 40 km and shows no emissions in the blue jet altitude range even for strong CG discharge. For blue jets, one can expect a wide range of jet velocities and durations of the emissions at different altitudes.

This model also has difficulties to explain unique jet features and more comprehensive work is required for getting further information.

4.3. Attachment-controlled ionizing wave concept :

Sukhorukov *et al* [14] have developed the blue jet dynamics in terms of a "streamer-shaped' ionizing potential wave as suggested by Raizer [39]. The ionizing wave moves upwards through an electron avalanche in the front due to the downward electric field, resembling the anode-directed negative steamer. The source of the background electric field is comparable to IC discharge. On the basis of the available blue jet observations the geometry of the model is suggested [10]. Balloon observations of the charge distribution in the anvils [40], is schematically presented in Figure 1.

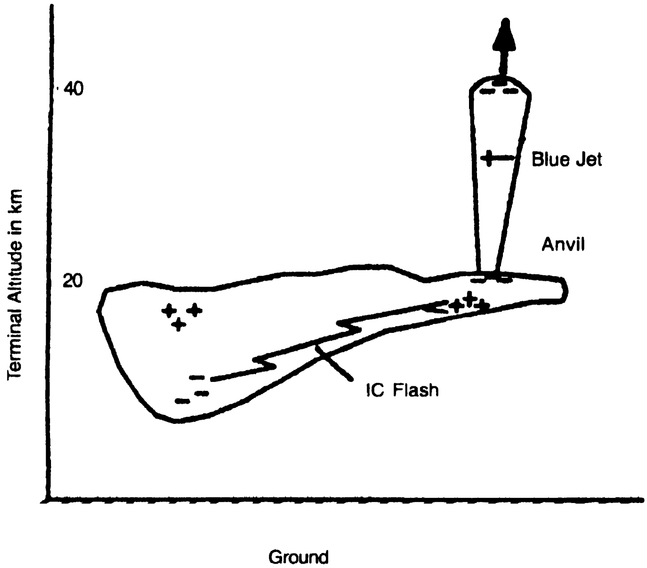

Figure 1. A schematic diagram of the blue jet model, showing the charge distribution in the anvils.

In the model, the background field is a fraction of the breakdown threshold E_c at which the ionization rate equates the rate of electron attachment to molecules. The negative charge strengthens the upstream field towards the front. In the steady state the wave front is fixed at $\approx E_c$ and the electric field E in the wave front can slightly exceeds E_c. As soon as E exceeds E_c, the ionization sharply increases the electron density. This, in turn, reduces the value of E below E_c due to the charge screening inside the dense plasma.

5. Blue jets *vis-à-vis* lightning

Some significant blue jets have reported in active thunder cells near the tri-state area of Arkansas, Texas and Oklahoma. Analysis of IC and CG flash rates in the cells from the TV fields revealed extraordinary rates of 200 flashes/min to 300 flashes/min. Wescott *et al* [12] in his study reported a related phenomenon called 'blue starters' that occurred in the same two storm areas. They compared the occurrence of negative CG lightning flashes to a distance of 50 km of each blue starter and observed that the mean rate of flashes following the events dropped considerably and did not recover to the pre-event flash rate for 2.25 seconds. It was noted that the mean negative CG flash rate is about 0.5 s. Thus the 2.25 s drop in the rate is the equivalent of one missing CG flash. Based on one missing CG lightning stroke the mean energy deficit implied by the change of slope was estimated to be 10^9 J [41]. In the latter investigation Wescott *et al* [32] further performed an identical analysis of lightning flash rates immediately before and after the blue jets. They compared the difference in time Δt between 27 blue jets, which were neither preceded nor followed by another blue jet or a blue starter within ±3 s, and negative CG flashes during the interval for ±5 s and within different radii. Figure 2 exhibits the cumulative flash rate to a distance of 15 km from the event. A change in slope in the cumulative distribution before and at the time of the event is seen in the figure. It was reported that there are more flashes prior to the jet than after it. If the subset of flashes within 10 km of the blue jet is considered it is seen that the ratio of flashes prior to the jet to those after the jet is 2 : 1.

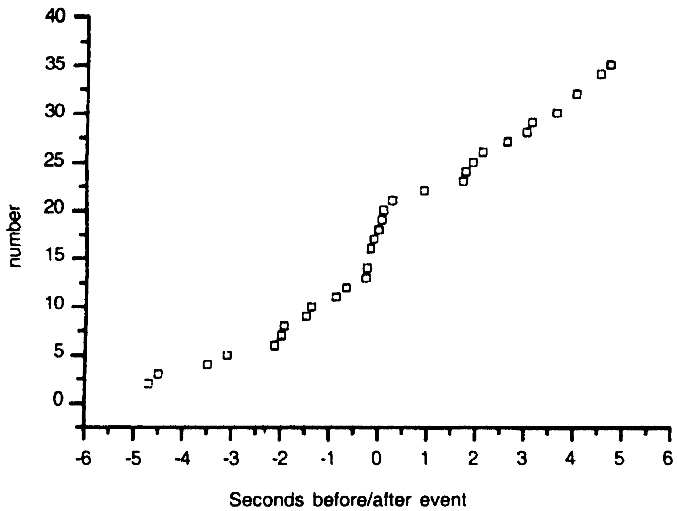

Figure 2. Cumulative distribution of negative CG flashes of 27 blue jets (after Wescott *et al* 1998)

The results indicate that there is a significant difference between the cumulative CG flash distributions of blue jets and blue starters. For the blue jets, the rate of negative CG flashes within 15 km doubles in the 1 s interval immediately before the jet occurs. Also for the same area of 30 km radius around jet and starters the flash rate is about 25% higher for jets suggesting that more charge transfer to the ground precedes jets than starters [32]. Moreover, their observation of a single blue jet over the thunderstorm in Kansas two nights later is in agreement with the conclusion that blue jets are not associated with positive CG flashes and that they occur in areas of negative CG flashes but are not accompanied by a particular flash.

Two groups of sprites were noted within 2 min before the interval of the blue jets, and three groups of sprites were repored during the interval and one just after the interval. The sprites were identified about 300 km east of the area of the blue starters and blue jets, and were generally associated with a +ve CG stroke within 50 km. These findings were in good agreement with the observations of Boccippio *et al* [42].

6. Discussion

All the models of the blue jet postulate large background quasi-electrostatic fields above the thundercloud. One of the various models proposed the pre-discharge model needs the largest fields while for the runaway breakdown model it is smallest. Significantly the direction of the background field is upward in the pre-discharge model and downward in the others. Sukhorukov [43] suggested that transient electric fields of both orientations may arise even simultaneously in different space-time regions following intra cloud, cloud-to-ground, inclined cloud-to-ground positive and negative discharges and their combinations. The presence of jets of both polarities may not be excluded, analogous to the existence of negative and positive CG lightnings. It is, of course, true that blue jets are very rare events in comparison with conventional CG and IC flashes and might be associated with exceptional thundercloud conditions and flashes [40,41]. We consider that special care must be given while investigating high-altitude IC discharges as high-altitude intra cloud activity seems to be particularly important for blue jets.

According to the runaway breakdown model as proposed by Taranenko and Roussel-Dupre [16], the primary emission due to electron impacts appears within 6 μs over the entire altitude range of the blue jet and lasts for about 0.13 ms while the long-time emission for a duration of 300 ms is due to the recombination of ions. If electric fields much lower than the conventional breakdown threshold are sufficient for the runaway breakdown model of the jet, then the corresponding red-to-blue ratio should differ from that predicted in the model by Sukhorukov *et al* [14], as in that case the detached electrons can not be heated sufficiently in the body of the blue jet. On the other hand, the model by Pasko *et al* [13] predicted that the intensities of the first and second positive bands of N_2 are more or less similar, in contradictory to the model by Sukhorukov *et al* [14] who suggested that the second positive band dominates over the entire range of the jet altitudes. Interestingly, the difference in the brightness of the jet between these two models is four order of magnitude approximately.

The dynamics and electrostatic field distribution within a thunderstorm anvil are complicated in nature. Byrne *et al* [40] reported the results of two balloon flights carrying corona probes for measuring electric fields. The balloons are allowed to pass through the anvil upstream of the precipitation core and measured extensive regions of both net negative and positive charges. They observed the thickness of screening layers to be nearly an order of magnitude higher than calculated in previous models.

7. Suggested problems and conclusion

Measurements of the jet and starter optical spectra at varying altitudes would provide important information on the elecrtron energy distribution. However, owing to strong sensitivity of emissions to the magnitude of the electric field the whole mechanisms of the formation of jets and starters have become two complicated. Though several models have been proposed from theoretical point of view, yet every model has its own advantages and shortcomings in explaining the documented features. At this stage a great number of observations are required to establish an advanced model of the blue jets in the light of the ideas to be gathered from further studies.

Interest has emerged in the possible electrochemical effects of sprites and jets on the stratosphere and mesosphere. Careful investigations are required to ascertain whether they may create locally or globally significant long lived electrochemical residues within the upper atmosphere. A detailed monitoring of the activity of severe thunderclouds during the experimental observation of blue jets is highly desirable. An association of the blue jets and starters with very large hail has also been stressed by Wescott *et al* [12]. While Changnon [44] reported a link between negative CG flashes and hail, Reap and MacGorman [45] and Curran and Rust [46] reported a link between positive CG flashes and hail. This interesting association of blue jets with hail and flashes of both negative and positive type [47] should be considered as a future problem.

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References

[1] A B Bhattacharya, M K Chatterjee, P Mali, N C Mondal and S K Sarkar *Indian J. Phys.* **74B** 113 (2002)

[2] R Bhattacharya, T Datta and A B Bhattacharya *Sci. & Cult.* **69** 437 (2003)

[3] O H Vaughan and B Vonnegut *Proceedings of the Eighth International Conference on Atmospheric Electricity, Uppsala, Sweden,* 383 (1988)

[4] R D Franz, R J Nemzek and J R Winckler *Science* **249** 48 (1990)

[5] W A Lyons *Geo. Res. Lett.* **21** 875 (1994)

[6] D D Sentman and E M Wescott *Geo. Res. Lett.* **20** 2857 (1993)

[7] W L Boeck, O H Vaughan, R J Blakeslee, B Vonnegut, M Brook and J McKune *J. Geophys. Res.* **100** 1465 (1995)

[8] E Huang, E R Williams, R Boldi, S Heckman, W A Lyons, M Taylor, T E Nelson and C Wong *J. Geophys. Res.* **104** 16943 (1999)

[9] D D Sentman and E M Wescott *Phys. Plasmas* **2** 2514 (1995)

[10] E M Wescott, D D Sentman, D Osborne, D Hampton and M Heavner *Geo. Res. Lett.* **22** 1209 (1995)

[11] A I Sukhorukov and P Stubbe *J. Atmos. Sol. Terr. Phys.* **60** 725 (1998)

[12] E M Wescott, D D Sentman, M H Heavner, D L Hampton, D L Osborne and O H Vaughan (Jr.) *Geo. Res. Lett.* **23** 2153 (1996)

[13] V P Pasko, U S Inan and T F Bell *Geo. Res. Lett.* **23** 301 (1996)

[14] A I Sukhorukov, E V Mishin, P Stubbe and M J Roycroft *Geo. Res. Lett.* **23** 1625 (1996)

[15] R Roussel-Dupre and A V Gurevich *J. Geophys. Res.* **101** 2297 (1996)

[16] Y N Taranenko and R Roussel-Dupre *Geo. Res. Lett.* **23** 571 (1996)

[17] E M Wescott, D D Sentman, D L Hampton, M J Heavner, D L Osborne and J D Williams *EOS Trans. AGU* **75** 108 (1994)

[18] E M Wescott, D D Sentman, D L Osborne, D L Hampton and M J Heavner *Geo. Res. Lett.* **22** 1205 (1995)

[19] E M Wescott, D D Sentman, M J Heavner and D L Hampton *EOS Trans. AGU* **76** 105 (1995)

[20] T MacKenzie and H Toynbee *Nature* **33** 26 (1996)

[21] W H Everett *Nature* **68** 599 (1903)

[22] W L Boeck, O H Vaughan (Jr.) and R J Blakeslee *EOS Trans. AGU* **72** P21C-1 (1991)

[23] W L Boeck, O H Vaughan (Jr.), R J Blakeslee, B Vonnegut, M Brook and J McKune *Proc. Int. Aerospace Lightning Conf., NASA Conference Publ. 1058*, Cocoa Beach, FL, April 16-19, 8 (1991)

[24] D J Malan *Academie des Sciences* **November 3** (1937)

[25] S E Ashmore *Weather* **5** 331 (1950)

[26] C A Wood *Weather* **6** 64 (1951)

[27] B Vonnegut *Weather* **35(2)** 59 (1980)

[28] Jr. O H Vaughan and B Vonnegut *Weatherwise* **35(82)** 70 (1982)

[29] D Gales *Weatherwise* **35(82)** 72 (1982)

[30] B Vonnegut *Weatherwise* **37(2)** 61 (1984)

[31] O H Vaughan (Jr.) and B Vonnegut *J. Geophys. Res.* **95** 13179 (1989)

[32] E M Wescott, D D Sentman, M J Heavner, D L Hampton and O H Vaughan (Jr.) *J. Atoms. Sol. Terr. Phys.* **60** 713 (1998)

[33] T Datta, A Bhattacharya, R Bhattacharya, R Das, S De and A B Bhattacharya *Indian J. Radio Sp. Phys.* **34** 387 (2005)

[34] J J Lowke *J. Phys. D : Appl. Phys.* **25** 202 (1992)

[35] G J Fishman, P N Bhat, R Mallozzi, J M Horack, T Koshut, C Kouveliotou, G N Pendleton, C A Meegan, R B Wilson, W S Paciesas, S J Goodman and H J Christian *Science* **264** 1313 (1994)

[36] A V Gurevich, G M Milikh and R Roussel-Dupre *Phys. Lett.* **A165** 463 (1992)

[37] T C Marshall, M P McCarthy and W D Rust *J. Geophys. Res.* **100** 7097 (1995)

[38] T F Bell, V Pasko and U S Inan *Geo. Res. Lett.* **22** 2127 (1995)

[39] Yu P Raizer *Gas Discharge Physics* (Berlin Heidelberg : Springer-Verlag) 449 (1991)

[40] G J Byren, A A Few and M F Stewart *J. Geophys. Res.* **94** 6297 (1989)

[41] M A Uman *Lightning* (New York : Dever Publications) 298 (1987)

[42] D J Boccippio, E R Williams, S J Heckman, W A Lyons, I T Baker and R Boldi *Science* **269** 1088 (1995)

[43] A I Sukhorukov *J. Atmos. Terr. Phys.* **58** 1711 (1996)

[44] S A Changnon *J. Appl. Meteor.* **31** 587 (1992)

[45] R D Reap and D R MacGorman *Mon. Wea. Rev.* **117** 518 (1989)

[46] E B Curran and W D Rust *Mon. Wea. Rev.* **120** 544 (1992)

[47] E R Williams, S G Geotis and A B Bhattacharya *J. Atmos. Sci.* **46** 1173 (1989)